Space Weather Action Plan Goal 1:

Benchmarks for Extreme Space Weather Events

Objective: To specify the space weather conditions associated with the most severe events (once in 100 years) and the possible impacts on systems and technologies that our Nation depends on.

Benchmark Leads

Jeff Love (USGS) – 1.1 Geo-Electirc Fields

Elsayed Talaat (NASA) – 1.2 Ionoizing Radiation

Rodney Viereck (NOAA) – 1.3 Ionospheric Disturbances

Doug Biesecker (NOAA) – 1.4 Solar Radio Bursts

Tim Fuller-Rowell (CIRES/NOAA) – 1.5 Atmospheric Expansion

Participation from DOC, DOD, DOI, NASA, NSF, etc…

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Benchmarks

SWAP Goal 1:

1.1 Induced Geo-Electric Fields

- What could and extreme event do to our electric power grid?

1.2 Ionizing Radiation

- How severe could the radiation environment be for satellites and aviation

1.3 Ionospheric Disturbances

- How will extreme ionospheric conditions impact radio communication and satellite navigation

1.4 Solar Radio Bursts

- How could solar radio bursts impact radio communication and satellite navigation?

1.5 Atmospheric Expansion

- How severe could extremes in satellite drag become

Space Weather Action Plan

- Goal 1: Establish Benchmarks for Space Weather Events
- Goal 2: Enhance **Response and Recovery** Capabilities
- Goal 3: Improve **Protection and Mitigation** Efforts
- Goal 4: Improve **Assessment**, Modeling, and Prediction of **Impact** on Critical Infrastructure
- Goal 5: Improve Space Weather Services through **Advancing Understanding and Forecasting**
- Goal 6: Increase **International Cooperation**

Timeline

- Oct. 2015: Release of the Space Weather Action Plan
- Oct. 2016: Phase 1 Benchmark documents submitted
  - A quick turnaround analysis of current state of knowledge and initial estimates of the Benchmarks.
- Feb. 2017: Phase 1 Benchmark document released for public comment on the Federal Register
- 2018: Phase 2 Benchmark Documents to be delivered
  - A more rigorous analysis of the benchmarks.

Challenges

- Defining the one-in-a-hundred year storm.
  - Extrapolate from only the last 40-50 years of observations
    - Not sure of the magnitudes
    - Are there theoretical upper limits?
    - Some elements may not scale in a predictable way
  - Use of the Carrington event of 1859
    - Very little data
- Complex interactions between all elements of the space environment
  - Sun, solar wind, magnetosphere, ionosphere, thermosphere, lower atmosphere.
- Converting environmental parameters into user impacts.

Benchmark 1.1 - Geo-Electric Fields

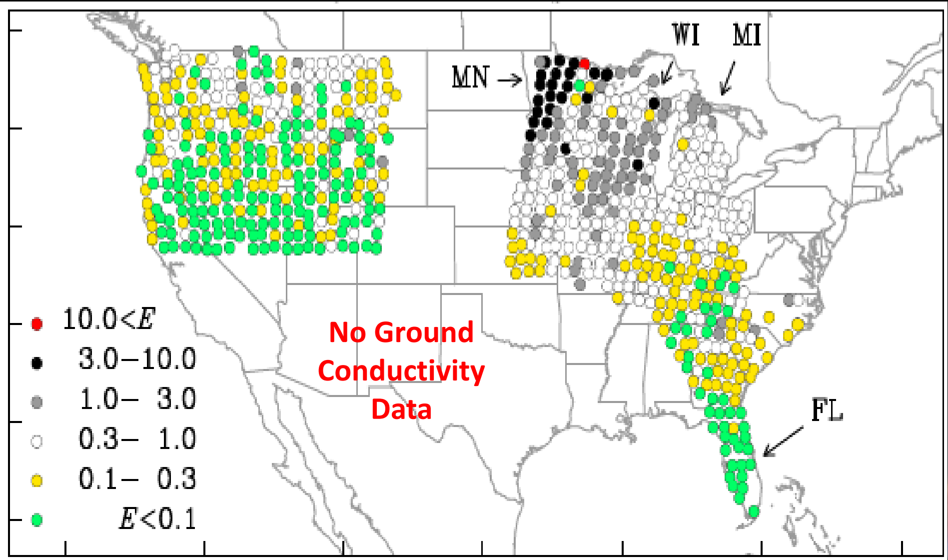
- Establishing estimates of extreme geo-electric fields will help designers and operators of electric power systems prepare for these events.

- Time-varying geomagnetic fields, during geomagnetic storms, create geo-electric fields in Earth's electrically conducting interior.
  - Intense geomagnetic storms induce large geo-electric fields
    - Drive quasi-direct currents in electric-power grids
    - Interfere with grid operation, damaging transformers, or cause power outages.
- Geo-Electric field strength depends on two things:
  - The strength of geomagnetic fluctuations
  - The 3-D conductivity of the ground

1.1 Geo-Electric Field Issues

- Extreme Regional Variability (conductivity and latitude)
  - In northern Minnesota, amplitudes exceed 14.00 V/km, while just over 100 km away, amplitudes are only 0.08 V/km.
  - Florida rarely exceeds 0.1 V/km
- Amplitudes of higher frequency fluctuations cannot be reasonably estimated from the existing data
- Lower frequency harmonics, or those persisting for long periods of time, will generally yield smaller geo-electric amplitudes,

Once-per-century geo-electric exceedance amplitudes, for north-south geomagnetic variation at 240 seconds (and over 600 seconds). No estimates are available outside of survey sites shown.

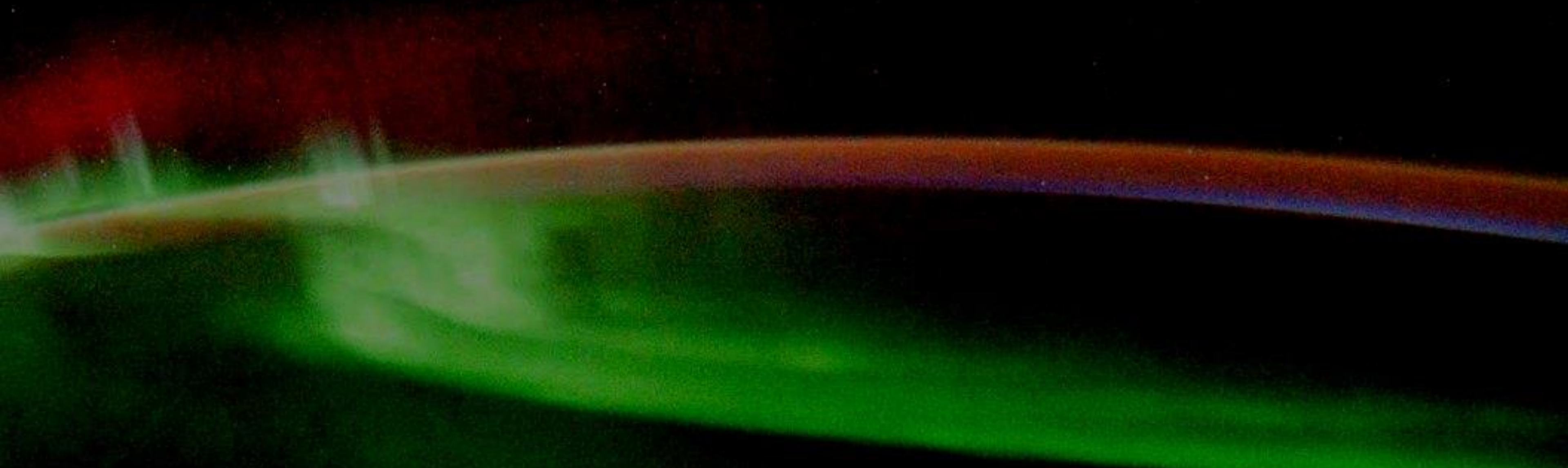


Lack of ground conductivity data prevents accurate estimates of geo-electric fields over much of the USA.

1.1 Geo-Electric Field

- Worst Case Observed: 14 V/km
  - NERC Worst Case Guidance: 8 V/km
  - March 89 (Quebec): 2 V/km

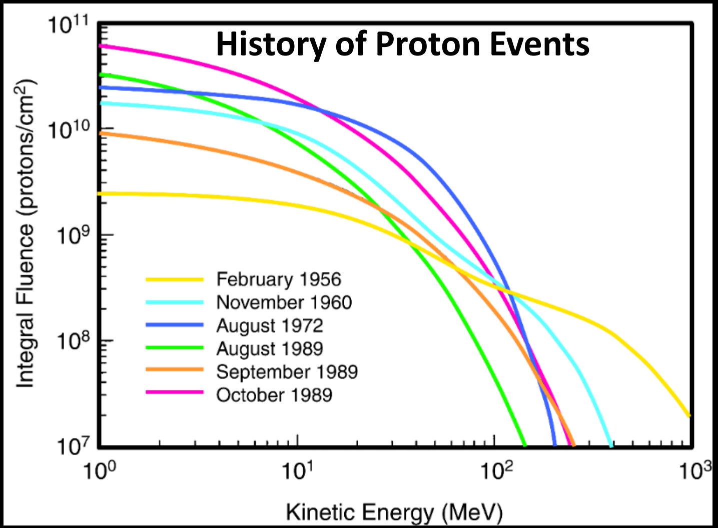
- Estimates of largest Geo-Electric fields will be highly location-dependent.

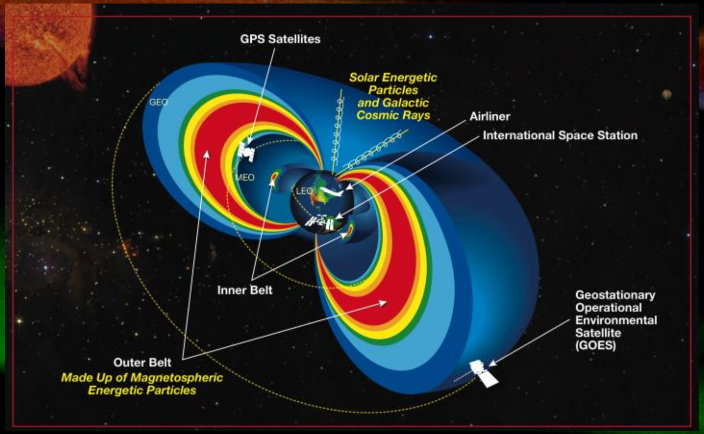


Benchmark 1.2 - Ionizing Radiation

Estimates of extreme ionizing radiation will provide guidance for protecting for humans in space and in aviation and help satellite designers and operators mitigate impacts. Ionizing radiation also impact radio communication (Benchmark 1.3)

- Solar Energetic Particles
  - Sudden enhancements of electrons, protons, and heavy ions near Earth
- Radiation Belts
  - Enhanced populations of electrons and protons surrounding Earth.
- Cosmic Rays
  - Background population of fully ionized (no electrons) particles including all elements of the periodic table.

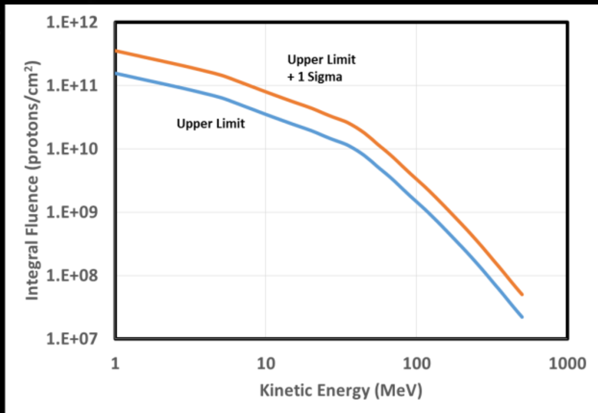




1.2 Ionizing Radiation

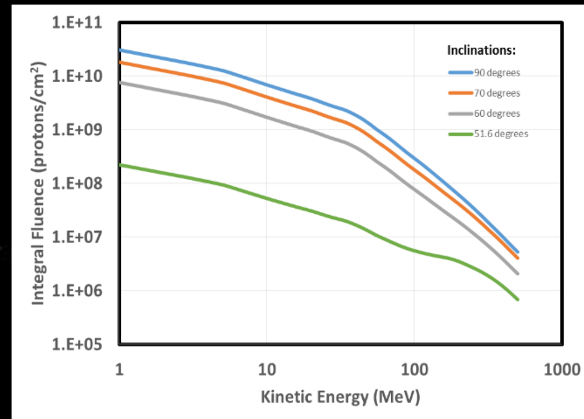
SEPs

GEO



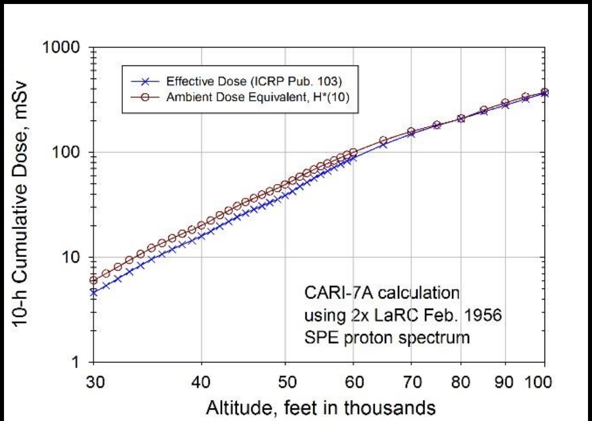
Solar proton event energy spectra for the statistical upper limit, plus one sigma.

LEO



Upper limit solar proton event energy spectra in LEO at an altitude of 400 km and spacecraft orbital angle of inclinations of 90, 70, 60 and 51.6 degrees.

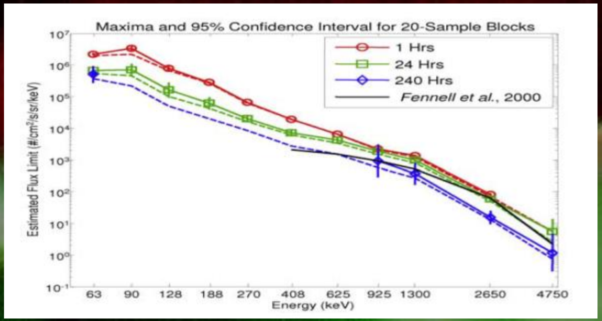
Aircraft



10-hour polar exposure at altitude, based on the LaRC event proton spectrum for the Feb 56 SPE.

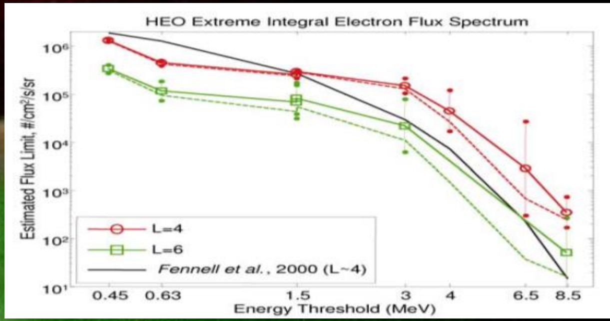
Radiation Belts

GEO



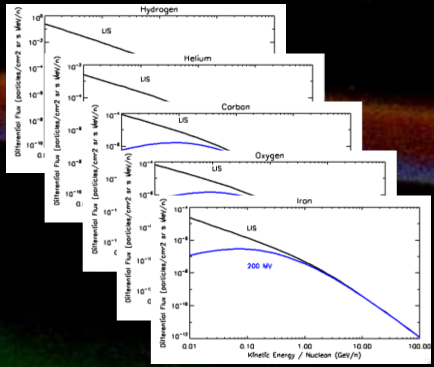
Radiation Belt worst case electron radiation belt flux estimates as a function of energy in GEO.

HEO



Radiation Belt worst-case fluxes versus energy are shown for two locations in HEO.

Gallactic Cosmic Rays



For 1 in 100 year benchmark the force-field modulation was slightly more permissive than those approximated for current conditions.

1.2 Ionizing Radiation

- Solar Particles

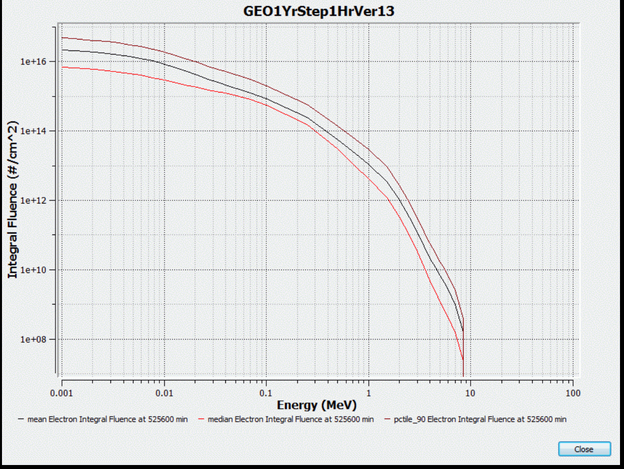
Solar Proton Event Integral Fluence (p/cm^2)					
Energy (MeV)	GEO	LEO 400 km, 90°	LEO 400 km, 70°	LEO 400 km, 60°	LEO 400 km, 51.6°
10	3.5×10^{10}	6.9×10^{9}	4.1×10^{9}	1.7×10^{9}	5.2×10^{7}
30	1.3×10^{10}	2.6×10^{9}	1.5×10^{9}	6.5×10^{8}	2.2×10^{7}
100	1.4×10^{9}	2.9×10^{8}	1.8×10^{8}	7.7×10^{7}	5.6×10^{6}
300	9.7×10^{7}	2.2×10^{7}	1.6×10^{7}	7.9×10^{6}	2.1×10^{6}

- Cosmic Rays

Differential GCR Flux (particles/cm^2 sr s MeV/n) at 1 AU, ϕ = 200 MV					
Energy/nucleon	Hydrogen	Helium	Carbon	Oxygen	Iron
10 MeV	1.3×10^{4}	1.7×10^{5}	6.1×10^{7}	5.3×10^{7}	1.2×10^{7}
30 MeV	3.2×10^{4}	3.7×10^{5}	1.3×10^{6}	1.1×10^{6}	2.5×10^{7}
100 MeV	5.3×10^{4}	4.7×10^{5}	1.7×10^{6}	1.5×10^{6}	2.9×10^{7}
300 MeV	4.1×10^{4}	2.7×10^{5}	9.9×10^{7}	8.9×10^{7}	1.5×10^{7}
1 GeV	1.2×10^{4}	6.9×10^{6}	2.6×10^{7}	2.4×10^{7}	3.7×10^{8}
30 GeV	1.7×10^{5}	8.1×10^{7}	3.3×10^{8}	3.0×10^{8}	4.9×10^{9}
100 GeV	1.2×10^{6}	5.4×10^{8}	2.4×10^{9}	2.1×10^{9}	3.9×10^{10}
300 GeV	6.4×10^{8}	2.6×10^{9}	1.3×10^{10}	1.1×10^{10}	2.3×10^{11}
1000 GeV	2.9×10^{9}	1.1×10^{10}	6.2×10^{12}	5.0×10^{12}	1.2×10^{12}

- Radiation Belts

Location	Energy	Electrons (units = $cm^{-2} s^{-1} sr^{-1}$)	
		1-in-100-Years Flux	Most Extreme Fluxes Observed (date)
GEO (GOES-W)[a]	>2 MeV	7.68×10^{5}	4.92×10^{5} (7/29/2004 - 1 in 50 yrs)
GEO (GOES-E)[a]	>2 MeV	3.25×10^{5}	1.93×10^{5} (7/29/2004 - 1 in 50 yrs)
		Upper Limit Flux (estimated)	Most Extreme Fluxes Observed (date)
GEO (LANL)[b]	2.65 MeV	5.9×10^{1}	5.1×10^{1} (7/30/2004)
	625 keV	4.1×10^{3}	3.4×10^{3} (7/29/2004)
	270 keV	2.0×10^{4}	1.6×10^{4} (6/5/1994)
HEO1 at L=4.0[b]	>8.5 MeV	3.5×10^{2}	2.4×10^{2} (8/30/1998)
	>4.0 MeV	4.5×10^{4}	2.6×10^{4} (8/5/2004)
	>1.5 MeV	2.6×10^{5}	2.4×10^{4} (8/30/1998)
HEO3 at L=6.0[b]	>630 keV	1.0×10^{5}	6.0×10^{4} (6/27/1998)
at L=4.0	>630 keV	4.5×10^{5}	4.3×10^{5} (8/29/1998)
at L=2.25	>630 keV	2.1×10^{5}	1.9×10^{5} (11/13/2004)

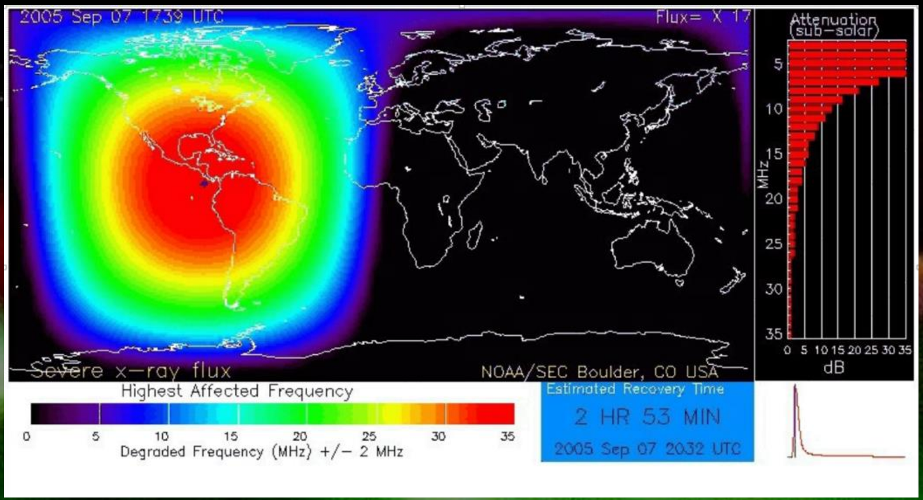


Estimates of 1 in 100 year flux levels for electrons estimated from the statistical AE9 reference model and scaled to GOES 2 MeV

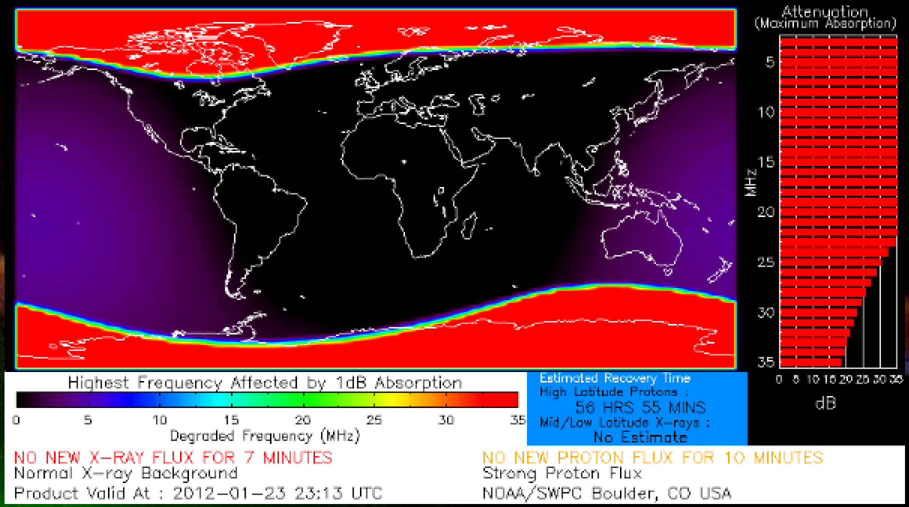
Benchmark 1.3 – Ionospheric Disturbances

- Solar x-ray flares: Block HF at the sub solar point
- Solar energetic protons: Block HF at high latitudes
- Polar structures and phenomena affect GPS/GNSS and communication
- Equatorial scintillation blocks GPS/GNSS and satellite communication
- Mid latitude variability can impact GPS/GNSS

Solar Flare and HF Communication



Solar Energetic Protons and HF Communication



1.3 Ionospheric Disturbances

Variability Issues and Geomagnetic Storm Impacts

- The state of the ionosphere has many dependencies.
  - Solar EUV irradiance
  - Solar X-Ray irradiance
  - Solar wind speed
  - Solar wind density
  - Interplanetary magnetic field
  - Conditions in the magnetosphere

  - Solar EUV irradiance
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  - Solar wind speed
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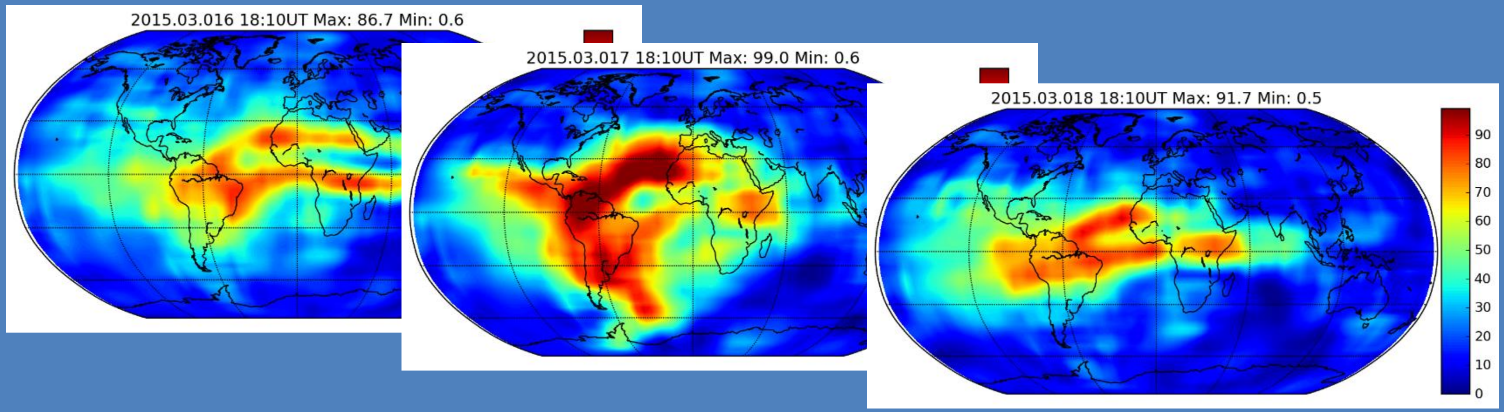
  - Interplanetary magnetic field
  - Conditions in the magnetosphere

- Observations of large storms do not cover the full parameter space.
- Models of the ionosphere have not been tested and validated under extreme conditions.

Observed TEC on 16, 17, 18 March 2015



New Global TEC Product Developed by Fuller-Rowell and Fuller-Rowell Using COSMIC and Ground GPS data

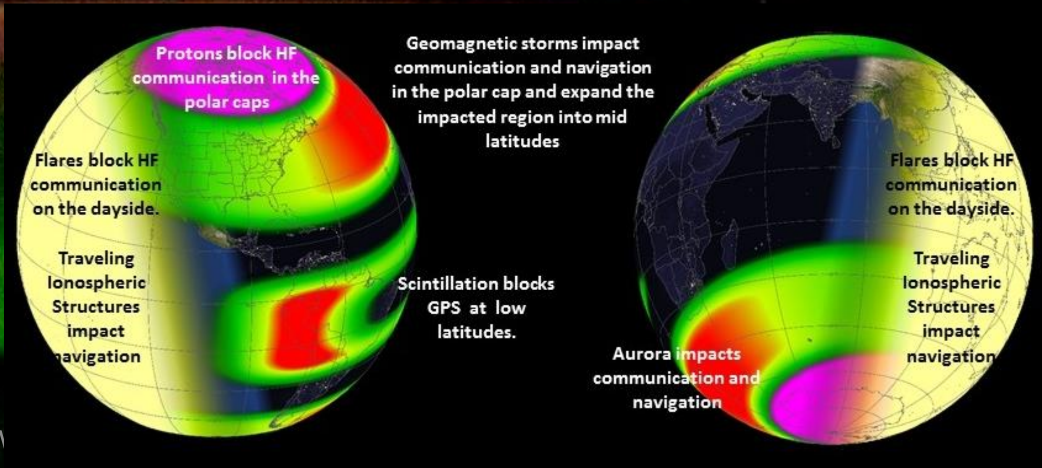
- Estimates of extreme conditions within the ionosphere and the resulting impacts on technologies could have errors of an order of magnitude.

1.3 Ionospheric Disturbances

Phenomenon	Magnitude	Location	Event	Duration	Impact	Technology Impact
Flare	X-Class Flare X- 28-40	Sunlit side of Earth	D-Layer Enhancement	Tens of minutes	Radio waves absorbed in the ionosphere up to 30 MHz	Loss of radar and communications in HF and VHF frequencies up to 40-50 Mhz
Proton	30 MeV Protons 1.2×10^9 /cm^2 sec	High and mid latitudes	D-Layer Enhancement	Several days	Absorbs RF signals from HF to VHF in the lower ionosphere	Loss of radar and communications in HF and VHF frequencies up to 30-40 Mhz
Geomagnetic Storms	Kp 9+	High and mid latitudes	Polar Cap and Aurora	10s of hours	Patches and plasma structures and ionospheric gradients refract radio waves	Degrades dual and single frequency GPS accuracy. Possible loss of signal lock
	Kp 9+	Mid latitude region on dayside of Earth	Traveling Ionospheric Disturbances and Storm Enhanced Densities	Hours	Large TEC enhancements (up to 200 TEC units) and strong gradients in TEC. Large regions of ionospheric depletion	Large GPS positioning errors (>10x normal). Degrades OTH radar performance. Loss of HF frequencies
		Latitudes +/-20 degs of geomag equator.	Equatorial Scintillation	A few hours after sunset	Large scale plasma depletions and associated small scale ionospheric structures observed just after sunset and generally up to midnight. Scintillation of transmitted radio signals.	Very large amplitude scintillations of GPS signals. Phase perturbations cause loss of signal lock in dual frequency GPS receivers. Possible total loss of HF communication.

Improvements

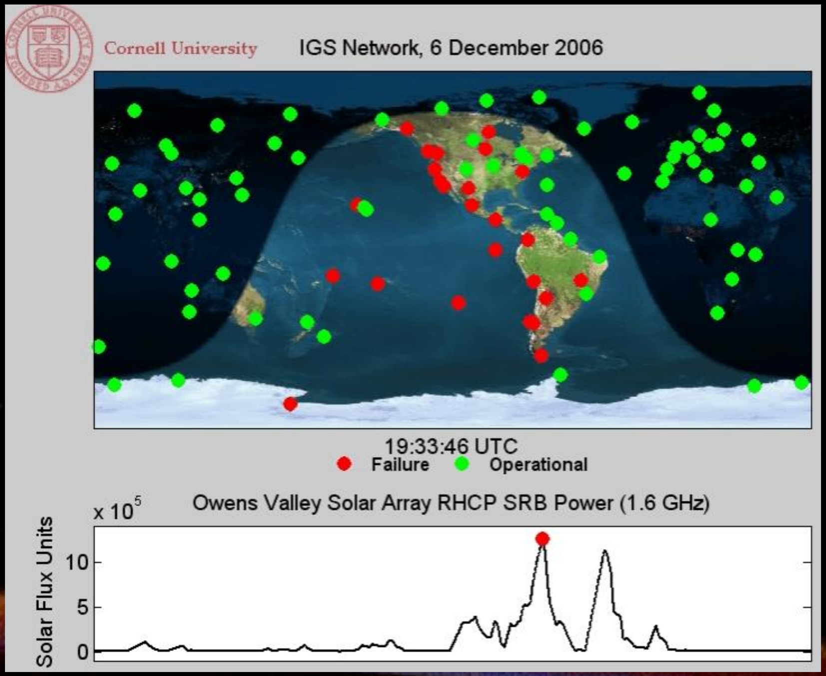
- **Better estimates of extremes in the input drivers**
- **improved empirical and physics based models**
- **More analysis of existing data**



1.4 Solar Radio Bursts

- Solar radio bursts are large enhancements in the solar noise produced by the sun usually associated with solar flares. They can affect a large range of radio frequencies and can last for 10s of minutes.
- Solar Radio Bursts (SRB's) interfere with radar, communication, and tracking signals.
- In severe cases, SRBs can inhibit the successful use of radio communications and disrupt a wide rage of systems reliant on PNT services (GPS/GNSS)
- Frequency bands for our benchmarks

VHF	UHF	GPS	F10.7	Microwaves
0.03-0.3 GHz	0.3-3.0 GHz	1.176-1.602 GHz	2.8 GHz	4-20 GHz



30 minutes

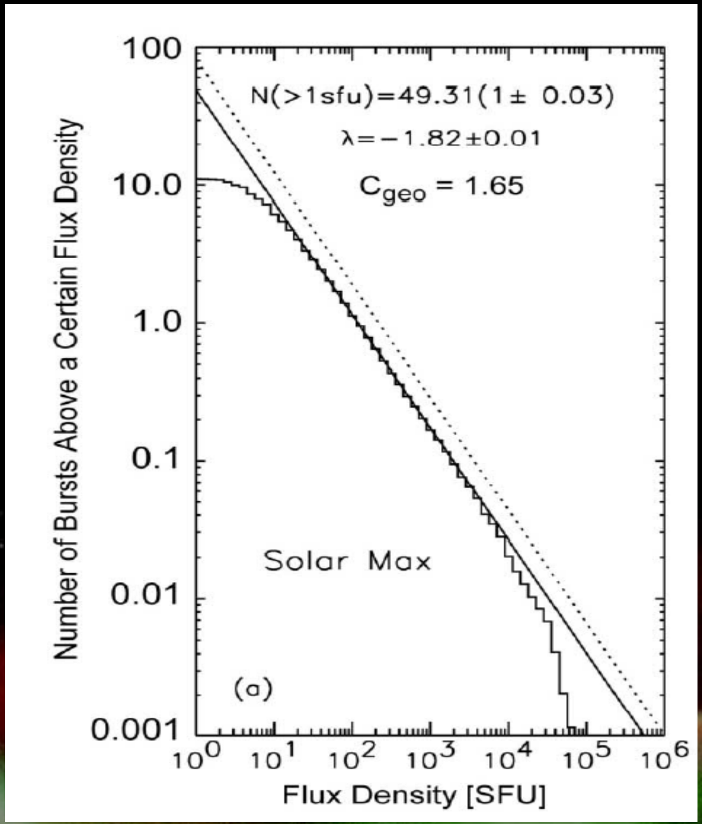
IGS – International GPS Service for Geodynamics

Peak Flux ~1.5×10^6 solar flux units (sfu)

1 sfu = 10^{-22} W m^{-2} Hz^{-1}

1.4 Solar Radio Bursts

Estimating the Frequency of Events



Nita *et al.* 2002

Cumulative number of SRBs per day at frequencies > 2,000 MHz

1 in 100 years is a rate of 2.74×10^{-5} bursts/day

Freq. Bands (MHz)	Freq. Band Name	Nita Freq. Bands (MHz)	RSTN Discrete Freq. (MHz)	100 Yr. Benchmark (sfu*)
30-300	VHF	100-900	245	2.8×10^9
300-3000	UHF	1000-1700	410 610	1.2×10^7
1176-1602	GPS	1000-1700	1415	1.2×10^7
2800	F10.7	2000-3800	2695	1.3×10^7
4000-20000	Microwave	4900-7000 8400-11800 15000-37000	4995 8800 15400	3.7×10^7

1.5 Atmospheric Expansion

Satellite Drag

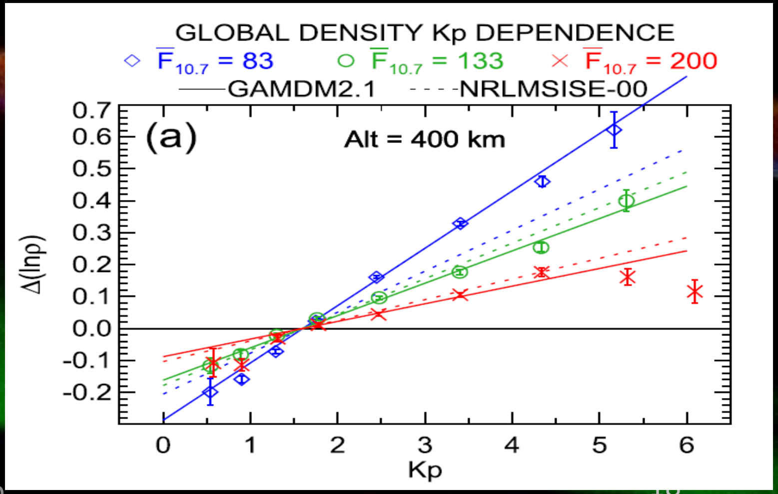
- Understanding extremes in satellite drag will help satellite operators avoid collisions and debris during extreme events.

- Changes in neutral density impacts satellite orbit prediction and collision avoidance.
- Neutral density responds to thermospheric heating as a result of…
  - Solar EUV (long term variability)
  - Solar EUV (flares)
  - Geomagnetic storms (CME’s)
- Additional Considerations:
  - Winds are important and can change apparent drag by up to 25%
  - Thermospheric structure is important.
- Benchmark includes neutral density/temperature, neutral winds (in-track and cross-track)
  - At altitudes of 250 km, 400 km, and 850 km

1.5 Atmospheric Expansion Issues

- Uncertainties:
  - How large are the drivers? Extremes in solar wind and magnetosphere and how they modulate the energy flow into the upper atmosphere and Joule heating rates
  - How does the atmosphere respond? The increase in nitric oxide during an extreme event is unknown and may modulate the temperature and density response
- Combined Effects:
  - Extreme storms are likely to occur at the same time as elevated EUV flux so the effects would be additive. The cumulative effect could be a factor 10 increase in density above previously observed storms.
  - Relative density changes are higher at low solar activity leading to greater chance of loss of the debris catalog, and reduced accuracy of debris orbit prediction.

Note: Due to large uncertainties and the likelihood of combining effects, the possible errors on some of neutral density estimates could be as large as 100%



1.5 Atmospheric Expansion: Satellite Drag

Driver	Parameter: Neutral Density	Percent Increase at Altitude relative to reference		
		250 km	400 km	850 km
Solar EUV* $F10.7/F10.7_{81}$: 390/280 Ref: $F10.7/F10.7_{81}$: 240/200	100-year	50%	100%	200%
Solar EUV* $F10.7/F10.7_{81}$: 500/390 Ref: $F10.7/F10.7_{81}$: 240/200	Theor. Max.	100%	160%	300%
Solar Flare X30	100-year	-	75%	-
Solar Flare X40	Theor. Max.	-	135%	-
Geomag. Storm** Ref: Halloween	100-year		400%	
Combined: EUV, flare, CME	100-year		900%	
* Reference model MSIS ** Reference model CTIPe				

- Improvements
  - Better estimates of extremes in the input drivers
  - improved empirical and physics based models
  - Better drag coefficients in He atmosphere above 600 km.

Summary

- Initial benchmark assessments are complete
  - Community feedback received.
- There are large uncertainties in several areas
- Uncertainties can be reduced and the Benchmarks refined with additional evaluation and model assessment.